

Impacts of logging roads on tropical forests

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15 **Impacts of logging roads on tropical forests**
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ABSTRACT

Road networks are expanding in tropical countries, increasing human access to remote forests that act as refuges for biodiversity and provide globally important ecosystem services. Logging is one of the main drivers of road construction in tropical forests. We evaluated forest fragmentation and impacts of logging roads on forest resilience and wildlife, considering the full life cycle of logging roads. Through an extensive evidence review we found that for logging road construction, corridors between 3 and 66 m (median 20 m) width are cleared, leading to a loss of 0.6 to 8.0 percent (median 1.8%) of forest cover. More severe impacts are increased fire incidence, soil erosion, landslides and sediment accumulation in streams. Once opened, logging roads potentially allow continued access to the forest interior, which can lead to biological invasions, increased hunting pressure and proliferation of swidden agriculture. Some roads, initially built for logging, become converted to permanent, public roads with subsequent in-migration and conversion of forest to agriculture. Most logging roads, however, are abandoned to vegetation recovery. Given the far-reaching impacts of the roads that become conduits for human access, its control after the end of logging operations is crucial. Strategic landscape planning should design road networks that concentrate efficient forest exploitation and conserve roadless areas.

KEY WORDS

Road ecology, forest management, reduced impact logging, invasions, forest resilience, forest degradation, deforestation, pantropical

22 ROADS HAVE A PROMINENT ROLE IN PUBLIC PERCEPTION OF TROPICAL FOREST DESTRUCTION.

23 Images of the fishbone-like patterns of deforestation along the Transamazonian Highway in

24 Brazil have become one of the symbols of global deforestation threats. This may be

25 comparable with the pictures of monotonous oil palm plantations and cattle pastures divided

26 by a sharp line from the heterogeneous canopy of old-growth forests. Such images are a

27 powerful visual representation of human dominance and destruction of tropical forests.

28 However, as with all iconic images, they create the danger that a single case is used as the

29 basis for generalizations about complex interactions occurring in tropical forest landscapes

30 around the world – narrowing the imagination of both the public and the scientific

31 community.

32 The global threats of road development are often underlined by the projection that by 2050,

33 more than 25 million more paved road lane-km will be built worldwide, with 90% being

34 located in non-OECD countries (Dulac 2013). It is not appropriate to apply this prediction

35 directly to tropical forests, where predominantly unpaved roads are built, but roads are now a

36 prevailing feature of tropical forests globally, often due to widespread selective logging

37 activities. Remote sensing analyses have documented the expansion of logging road networks

38 throughout the tropics (e.g. Laporte *et al.* 2007, Gaveau *et al.* 2014, Ahmed, Souza, *et al.*

39 2013, Kleinschroth, Healey, Gourlet-Fleury, *et al.* 2016, Arima *et al.* 2008). Annual growth

40 rates are reported of up to 40 km of new roads per 10 000 km² of forest area (Brandão &

41 Souza 2006), sometimes unconstrained by the boundaries of officially protected areas

42 (Curran *et al.* 2004). Logging road networks, however, are highly dynamic in space and time

43 and their impacts might differ from other types of road in tropical forests (Kleinschroth *et al.*

44 2015). Surprisingly, a comprehensive review of impacts for the full “life-cycle” of logging

45 roads is largely missing.

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2
3 46 Fifty-three percent or 400 million hectares of the natural tropical permanent forest
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5 47 estate comprises (timber) production forest (Blaser *et al.* 2011). In the face of such
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7 48 widespread logging activities in tropical forests worldwide, consensus is growing about the
8
9 49 importance of the state of logged forests for their conservation value and the need to reduce
10
11 50 logging impacts to maintain major ecosystem services while allowing timber extraction for
12
13 51 economic reasons (Putz *et al.* 2012, Edwards *et al.* 2011). Logging roads have a particular
14
15 52 role in reducing impacts of tropical logging as they are the most costly, damaging and visible
16
17 53 part of selective logging activities. At low harvest levels (< 4 trees per ha), which are
18
19 54 common in many tropical regions, damage from road construction is much higher than from
20
21 55 tree felling (Gullison & Hardner 1993, Sist *et al.* 2003).
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26 56 Identifying tropical forest degradation is difficult, especially on a larger scale. Roads,
27
28 57 as the most visible indicator of human activity in tropical forests, are therefore often used as
29
30 58 the main indicator to estimate the global extent of forest degradation (see e.g. Lewis *et al.*
31
32 59 2015). The underlying logic is that forest areas that are not accessible by roads are considered
33
34 60 to be the least degraded because they provide habitat that is not immediately affected by
35
36 61 human activities on an industrial scale (Potapov *et al.* 2008). The possibility that responsible
37
38 62 forest management can avoid degradation is not taken into account in these approaches (Putz
39
40 63 *et al.* 2012). “The first cut is the deepest” (Laurance *et al.* 2015) and logging roads are often
41
42 64 the first to penetrate old-growth forests, opening what has been termed “a Pandora’s box” of
43
44 65 environmental problems (Laurance *et al.* 2009). Road building strategies therefore advocate
45
46 66 to concentrate road building (Laurance *et al.* 2014) and to set-aside high conservation-value
47
48 67 forest areas from logging to keep them entirely road-free (Clements *et al.* 2014). More
49
50 68 specific evidence, however, is needed about which impacts are directly associated with roads
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52 69 built for logging activities. Many publications do not make a distinction between roads built
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54 70 and used for logging and those for other purposes such as public transportation (e.g. Barber *et*
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3 71 *al.* 2014, Ahmed, Ewers *et al.* 2013, Pfaff *et al.* 2007). The majority of logging roads differ
4
5 72 greatly from other linear forest clearings for infrastructure, in that they are used only for a
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7 73 certain purpose and for a limited amount of time.
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10 74 Where logging takes place in industrial concessions, logging companies are often the
11
12 75 only official users of logging road networks, which are built and maintained according to just
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14 76 the companies' immediate economic interests (solely to provide access to the forest for heavy
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16 77 machinery and to allow trucks to transport harvested trees to timber processing sites).
17
18 78 Typically, such roads are unpaved but the investment in their engineering is based on a
19
20 79 network hierarchy with at least two different levels: (i) a few primary roads built to
21
22 80 permanently access the forest concession as a whole; (ii) many secondary "dead-end" roads,
23
24 81 branching off the primary roads and only built for use in a short period of timber harvesting
25
26 82 from a limited forest area (months to a few years) before being abandoned. Skid trails, used
27
28 83 to extract logs by dragging them with heavy machinery from their felling site to "logging
29
30 84 yards" (or "landing sites") on the roadside, where they are lifted onto trucks, are typically
31
32 85 much shorter and narrower than the forest roads constructed for use by trucks, and are often
33
34 86 under the canopy of adjacent trees. They constitute a different category of environmental
35
36 87 impact on the forest and are not included in this review.
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42 88 Habitat fragmentation is one of the main impacts of roads in tropical forests.
43
44 89 However, there is a lack of evidence review about aspects of fragmentation related to road
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46 90 width, forest cover cleared for road construction, and about how animal movements are
47
48 91 affected. To meet this need for evidence, it is crucial to assess logging roads not simply as a
49
50 92 static component in the landscape but instead to consider their whole "life cycle". This
51
52 93 includes the intense activity during the construction phase, the main primary use phase (often
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54 94 timber extraction), followed by alternative fates such as road abandonment followed by
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56 95 gradual recovery of forest cover *versus* maintenance of the road as a more permanent
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landscape feature due to continuing use, sometimes associated with upgrade to a public road. Given the dynamic nature of tropical forests and the complexity of current degradation and conversion processes, information is scarce about the relative importance and persistence of each phase in the road life-cycle. We evaluated the short- and long-term impacts of logging roads on tropical forest vegetation, fauna, soil and hydrology by addressing the following questions: (1) To what extent are logging roads fragmenting forests by dissecting formerly connected forests into smaller units? (2) How do roads affect forest resilience and wildlife populations? (3) How long-lasting are each of these impacts in dynamic tropical forest environments? (4) How commonly do roads built for logging undergo a transition to public roads that can eventually lead to large-scale deforestation? (5) How can such impacts be reduced through preventative or *post hoc* interventions?

METHODS

Given the relatively wide scope of this evidence review, we considered all literature dealing with the impacts of roads initially built for logging in tropical forests around the world. We conducted a comprehensive database search in Web of Science and CAB-direct, using the keywords: “logging” AND “road*” AND “impact” AND “tropic*”. This generated 156 results for Web of Science and 393 for CAB Direct. In an iterative process, we broadly selected relevant publications based on title and abstract. These selected papers led to further sources through backward tracking (based on their reference lists) and forward tracking (based on subsequent papers in which they have been cited). Other reviews on related subjects (Kleinschroth, Gourlet-Fleury, *et al.* 2016, Laurance *et al.* 2009, Hawthorne *et al.* 2011, Picard *et al.* 2012) proved to be particularly useful in identifying additional publications. All these references were added to our existing literature database (see data

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2
3 120 availability statement below), covering more than 1300 publications related to road ecology
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5 121 and tropical forest management. This database allowed comprehensive full text searching – in
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7 122 addition to that enabled by online search engines. We searched all documents for the
8
9 123 keywords “logging” and “road”. All selected documents then underwent a critical appraisal
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11 124 of the methods and results used in each study. Inclusion criteria were that they must present
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13 125 original evidence of impacts based on empirical methods or first-hand observations. The
14
15 126 relevant information was extracted and grouped into thematic categories. In parallel, we
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17 127 extracted quantitative results for all road width measurements of logging roads and the
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19 128 proportion of forest area that had been cleared for road building (i.e. disturbed area as a
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21 129 percentage of overall logged area).
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26 130 The search strategy resulted in 178 publications that were used to provide the
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28 131 evidence for further review. Overall, the analysed studies showed strong contrasts in the
29
30 132 methods used, with a dominance of anecdotal observations made on individual roads. Given
31
32 133 these empirical limitations and strong differences in focus, we did not apply any weighing
33
34 134 between the studies. The quantitative results are therefore only indicative. Many sources do
35
36 135 not document how exactly they measured road corridor width, but the most straightforward
37
38 136 way on the ground is to measure the distance between the stems of the two closest trees on
39
40 137 either side of the road track (Figure 1). We did not include measurements entirely based on
41
42 138 remote sensing, as optical sensors (in contrast to LIDAR) only allow the estimation of canopy
43
44 139 opening from above. Evidence reviews based on published literature carry a risk of
45
46 140 publication bias (Huntingdon 2011), due to failure of researchers to publish non-significant or
47
48 141 non-anticipated results. We have no evidence for such publication bias but noted that most of
49
50 142 the published studies reported negative effects of roads on the forest.
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144 RESULTS AND DISCUSSION

145 FRAGMENTATION IMPACTS. —The first and most obvious road impact is linear clearing of
146 forest cover. Road tracks (Figure 1) used by logging vehicles had a median reported width of
147 6.4 m (primary roads) and 5.1 m (secondary roads). The range of track widths is relatively
148 small (3 m to 7.9 m, Table 1) but most logging road construction involves the felling of trees
149 in much wider corridors than just the road track itself. This is due to traffic safety reasons and
150 in order to let the sun dry the road surface after rain (Sessions 2007). Overall medians for full
151 corridor width are 24.85 m for primary and 15.1 m for secondary roads but there are strong
152 regional contrasts. Few measurements are available for Asia, but secondary logging roads in
153 tropical America (range 3 – 10.5 m) have generally narrower corridors than in Africa (15.1 –
154 66.6 m, Table 1).

155 The proportion of forest that is cleared for road construction depends on both road
156 length density and road width. The most commonly used reference area for this proportion is
157 the total logged area, for example that delimited by annual logging blocks. The global median
158 percentage is 1.7 percent of the forest area, with the range of values being 0.6–8 percent in
159 America, 0.74–6.4 percent in Africa and 3.3–4.8 percent in Asia (Table 2). The full clearing
160 of forest for road construction leads to carbon emissions from destroyed biomass. A study in
161 East Kalimantan, Indonesia estimated road construction to account for 14% of all logging-
162 related carbon emissions (Griscom *et al.* 2014). These calculations account for the damage
163 that road construction causes to trees adjacent to the corridor (Iskandar *et al.* 2006, Johns *et*
164 *al.* 1996, Jackson *et al.* 2002). In a Central African study, the biomass recovered through
165 forest regrowth on road tracks abandoned at least 15 years previously accounted for only 6%
166 of the initial amount (Kleinschroth, Healey, Sist, *et al.* 2016).

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3 167 IMPACTS ON SOIL AND HYDROLOGY. —The construction of logging roads is
4
5 168 accompanied by the exposure of subsoil, as topsoil is mostly scraped away. Traffic and
6
7 169 machine use cause additional compaction of the soil on the road track (Woodward 1996).
8
9 170 This soil degradation can have important consequences *in situ* and *ex situ*. *In situ* effects are
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11 171 increased bulk density (Donagh *et al.* 2010, Guariguata & Dupuy 1997) and reduced soil
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13 172 respiration (Takada *et al.* 2015), which affect the “soil natural capital”, reducing ecosystem
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15 173 services of nutrient retention and cycling, soil formation and primary productivity. Such
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17 174 supporting services are of great importance for vegetation recovery on the road track, thus
18
19 175 determining the time duration of many other road impacts. In combination with steep terrain
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21 176 and high rainfall, soil exposure and compaction lead to increased rates of surface water runoff
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23 177 (Douglas 2003, Ziegler *et al.* 2007), which can result in severe erosion (Clarke & Walsh
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25 178 2006, Sidle *et al.* 2004) and high rates of sediment export (Negishi *et al.* 2008). Sediment has
26
27 179 far reaching *ex situ* consequences on aquatic habitats in down-slope streams. Greatly
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29 180 enhanced sediment yields have been quantified in Malaysian streams, with levels 14 times
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31 181 higher after logging than before, thus affecting water quality and streamflow through
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33 182 accumulation of sediment and wood debris (Gomi *et al.* 2006).
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39 183 After abandonment, road track soils can remain compacted for a long time. In a study
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41 184 in Costa Rica, three out of four roads were still compacted >10 years after abandonment
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43 185 (Guariguata & Dupuy 1997). In Central Africa, abandoned road tracks showed a 36%
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45 186 decrease in compaction after 15 years but this was still 55% higher than the level of the
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47 187 adjacent forest (Kleinschroth, Healey, Sist, *et al.* 2016). Regarding erosion and hydrology it
48
49 188 is notable that most studies (with the exception of some reports from Guyana by Steege *et al.*
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51 189 1996) have been conducted in South-East Asia, especially Malaysia, where logging
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53 190 intensities are particularly high and the steep terrain is more prone to erosion than in the
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55 191 lowland basins of the Congo and the Amazon rivers. In Sabah, erosion, sediment transport
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3 192 and landslides show episodic peaks for a long time after logging, depending on the
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5 193 occurrence of extreme weather events (Douglas *et al.* 1999, Sidle *et al.* 2006). Early studies
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7 194 that compared sediment yields before and one year after logging showed contradictory results
8
9 195 ranging between 3.6 times higher values (Douglas *et al.* 1992) and no difference at all
10
11 196 (Douglas *et al.* 1993). However, a longer-term study showed that sediment sources 21 years
12
13 197 after logging were mainly road-linked (Walsh *et al.* 2011). The effects of gullying, landslides
14
15 198 and collapses of roadfill material contribute to the long-term degradation of soils and
16
17 199 watercourses in heavily logged forest areas (Chappell *et al.* 2004). Road crossings of
18
19 200 watercourses can make a large contribution to the sediment load, as bridge abutments are
20
21 201 often simply filled with soil that erodes over time as slopes revert back to their angle of
22
23 202 repose (Wells 2002). Although sediment production from road surfaces can be reduced by
24
25 203 86% within one year due to establishment of a herb layer (Negishi *et al.* 2006), recovering
26
27 204 vegetation is estimated to take 20 years to reach a sufficient root strength that to prevent
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29 205 landslides on roads in steep terrain (Sidle *et al.* 2006).
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34 206 Streams are often physically altered wherever they are crossed by logging roads with
35
36 207 inadequately constructed or maintained bridges or culverts, thus damming up the stream and
37
38 208 creating artificial ponds. A particular problem is caused when road bridges and culverts
39
40 209 constructed with logs collapse into streams after road abandonment (Chappell *et al.* 2004).
41
42 210 Recovery of stream water quality can be delayed by many years if sediment is temporarily
43
44 211 stored behind channel obstructions and released periodically (Douglas 1999). Obstruction of
45
46 212 streams has negative consequences for animal species that depend on fast flowing water and
47
48 213 surrounding vegetation that is intolerant of waterlogging, but at the same time it creates new
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50 214 habitats for other species (Schmidt *et al.* 2015).
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55 215 WEAKENED FOREST RESILIENCE. —Road impacts in forests can extend to a much
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57 216 greater area than just the corridor cleared for road construction. Edge effects may reach far
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217 into the adjacent forest, through desiccation resulting from exposure to wind and higher tree
 218 transpiration rates next to the open corridor (Kunert *et al.* 2015). Such desiccation effects
 219 may make an important contribution to the correlation between roads and fire occurrence
 220 (Nepstad *et al.* 1999, Adeney *et al.* 2009). Tree debris, accumulated at the roadside during
 221 road construction, may act as additional fuel for such fires (Laurance & Useche 2009). Roads
 222 may also influence fire regimes through increased fire ignition as a result of human activities
 223 that occur in the transportation corridor (Franklin & Forman 1987, Brando *et al.* 2014). On
 224 the other hand, to fight fires, road access is needed (Francis E. Putz, pers. comm.). Road-
 225 related fire-risk also decreases over time as shown by Siegert *et al.* (2001) for the exceptional
 226 fires that raged in Borneo during 1997-98. Sixty-five percent of the area within a 1000 m
 227 buffer around recently established logging roads was burned. In contrast, for old logging
 228 roads used at least six years earlier, the burnt area was only 16 percent.

229 There are substantial dangers of positive feedbacks between logging roads, fire
 230 occurrence and invasions of grasses and lianas (Veldman *et al.* 2009). In their function as
 231 corridors, logging roads can facilitate biological invasions. For example logging trucks have
 232 been shown to act as dispersal vectors for exotic grasses in Bolivia (Veldman & Putz 2010).
 233 Also, in South-East Asia, road construction and subsequent swidden agriculture facilitate the
 234 invasion of pyrogenic grasses such as the cogon grass, *Imperata cylindrica* (Putz & Romero
 235 2015). Shrubs have also been reported to spread along logging roads (Padmanaba & Sheil
 236 2014). The establishment of many invasive plants is favoured by the open canopy above the
 237 road (Costa & Magnusson 2002). Consequently the exotic herb species *Chromolaena*
 238 *odorata*, which is very abundant along open roads in central Africa, disappeared shortly after
 239 road abandonment due to growth of taller shading species (Kleinschroth, Healey, Sist, *et al.*
 240 2016). In the Congo Basin, recent El Niño-related fire events showed a clear positive
 241 correlation with the abundance of Marantaceae herbs (Verhegghen *et al.* 2016). These

indigenous herbs show long-lasting high abundance on abandoned logging roads (Kleinschroth, Healey, Sist, *et al.* 2016), which may explain many (but not all) observed fire outbreaks being located near permanent or recently abandoned logging roads in this region (Verhegghen *et al.* 2016).

Some studies also document negative impacts of animal invasions of forests along roads. The exotic little red fire ant, *Wasmannia auropunctata*, is reported to spread along logging roads in Gabon, potentially harming the vision of large mammals through its stings (Walsh *et al.* 2004) and forest anuran communities in Brunei were severely disturbed by the road-facilitated immigration of the predatory greater swamp frog, *Limnonectes ingeri* (Konopik *et al.* 2013).

WILDLIFE IMPACTS: “LANDSCAPES OF FEAR” AND DEFAUNATION. —Logging roads can have strong impacts on animal population dynamics. While in Australia public roads in rainforests have been associated with high numbers of road kill (Goosem 1997), we did not find any empirical studies that document large numbers of animals killed by logging road traffic. The more important impact of logging roads is that they can fragment animal habitats causing a change in animal behaviour. Open forest roads form a different habitat in terms of microclimate, and may expose animals to potential predators (Thiollay 1997) and a strongly increased likelihood of encounters with hunters. Roads thus present strong peaks in the “landscape of fear” for wildlife (Laundré *et al.* 2010). Forest specialist and understorey birds in particular are reported to avoid edges created by roads and not to cross them (Lees & Peres 2009, Laurance *et al.* 2004, Develey & Stouffer 2001, Laurance 2004). However, in a study by Laurance & Gomez (2005), radio-tracked birds only refrained from crossing roads when they were in open corridors of > 250 m width, which is uncommonly wide for logging roads (see above). It is therefore equivocal how far the sheer presence of a logging road inhibits animals of most species from crossing it. A study in Cameroon using track plots filled with

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3 267 substrates where animals leave traces that can later be associated with a species, suggest that
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5 268 duikers and apes might avoid crossing logging roads (Hoeven 2010). Correlations between
6
7 269 reduced animal population densities and proximity to roads have been found to be linked to
8
9 270 increased rates of hunting on and around roads (Van Vliet & Nasi 2008). That hunting is the
10
11 271 main factor has also been confirmed through studies comparing roads outside and inside
12
13 272 areas where hunting is effectively prevented. Examples are a fenced oil concession (Laurance
14
15 273 *et al.* 2006) and large national parks, where inside the protected areas roads did not affect
16
17 274 animal movement patterns, while outside they did (Blake *et al.* 2008).
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21 Unregulated hunting is now imperilling vertebrate species throughout the tropics
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23 276 (Bennett *et al.* 2002). This has even led to the widespread reporting of “empty” forests
24
25 277 (Redford 1992) that look intact from the outside but are actually depleted of major
26
27 278 components of their wildlife populations through hunting (Bennett & Robinson 2000,
28
29 279 Poulsen *et al.* 2011, Laurance *et al.* 2006). Increased levels of hunting have been noted near
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31 280 logging roads throughout the tropics (Theuerkauf *et al.* 2001, Laurance *et al.* 2006, Wong &
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33 281 Linkie 2013, Hall *et al.* 1997, Thiollay 1997, Brodie *et al.* 2015). In Central Africa especially,
34
35 282 bushmeat provides the most important source of protein for most forest-dependent
36
37 283 communities, who have been hunting for a long time (Nasi *et al.* 2008). The presence of
38
39 284 extensive road networks, however, has allowed the development of a new type of livelihood,
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41 285 that of specialized market hunters. Improved accessibility has extended the reach of the
42
43 286 transport chain, which has led to increased quantities of extracted bushmeat being supplied to
44
45 287 meet the increasing demand in urbanized areas further away from the forest (Wilkie *et al.*
46
47 288 2000). Logging company employees and other people settling around logging camps are
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49 289 further driving the demand for bushmeat (Bennett & Gumal 2001). Logging vehicles are
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51 290 frequently used to transport hunters, weapons and game, thus increasing the radius of
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291 defaunation around settlements deeper into the forest (Poulsen *et al.* 2009, Robinson *et al.*
292 1999).

293 Little is known about the persistence of hunting impacts after logging road
294 abandonment and for how long transport for commercial hunting remains possible. Hunters
295 on motorcycles might only be able to use logging roads up to 10 years after abandonment due
296 to collapsed bridges and vegetation recovery (Kleinschroth, Healey, Sist, *et al.* 2016). Roads
297 often continue to be used as footpaths after the end of logging activities, but evidence of the
298 effects of such footpaths on animal populations is ambiguous. Hall *et al.* (1997) showed that
299 footpaths are avoided by elephants (*Loxodonta africana*) in Democratic Republic of Congo,
300 while Brodie *et al.* (2015) showed no effect on mammal abundances of trails on abandoned
301 logging roads.

302 Human disturbance of habitats and animal populations can lead to changes in the
303 overall animal community structure. Changes in species richness and composition have been
304 shown for dung beetles inside road corridors (Hosaka *et al.* 2014, Yamada *et al.* 2014) and
305 for nocturnal animals within approximately 30 m on either side of road edges (Laurance *et al.*
306 2008). An impact on bird communities has been proposed by Mason (1996) and Thiollay
307 (1997) but could not be confirmed by Develey & Stouffer (2001). Also, for butterfly
308 communities, no evidence of community changes could be found (Willott *et al.* 2000).

309 While some roads provide a barrier to animal movement, others function as corridors
310 positively “facilitating” it. Animals may be attracted by roads as they provide connections,
311 orientation and food: Pumas (*Puma concolor*) and jaguars (*Panthera onca*) have been
312 identified as “trail walkers” on old logging roads in Belize (Harmsen *et al.* 2010); african
313 civets (*Civettictis civetta*) have been reported to use logging roads as preferred pathways and
314 hunting grounds in Africa (Ray & Sunquist 2001) and leopards (*Panthera pardus*) are
315 reported to make 20% of their movements following human paths (Jenny 1996). Also

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3 316 elephants (*Loxodonta africana*) feed on secondary vegetation growing on roadsides
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5 317 (Nummelin 1990, Barnes *et al.* 1997) and after road abandonment, recovering vegetation
6
7 318 provides a food source welcomed by gorillas (*Gorilla gorilla gorilla*) (Matthews & Matthews
8
9 319 2004). Puddles, which frequently develop in ruts and compacted tracks of logging roads,
10
11 320 provide surrogate habitats for anuran communities (Ernst *et al.* 2016).
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15 321 FOREST CONVERSION IMPACTS. —The issue of human invasion of tropical forest land
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17 322 is central to the issue of whether logged forests become degraded or not (Laurance 2001). In
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19 323 their function as access routes into formerly inaccessible forests, logging roads may not only
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21 324 facilitate illegal logging (Obidzinski *et al.* 2007) and hunting (Wilkie *et al.* 1992), but also
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23 325 conversion of forest land to agriculture. The construction of logging roads is often seen as the
24
25 326 first step in a sequence of increasing human impact on tropical forests that starts with
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27 327 selective exploitation of forest resources and then leads to forest degradation and eventually
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29 328 deforestation by conversion to agricultural land (Figure 2). In general, conversion of tropical
30
31 329 forests to agriculture can be divided into (i) small-scale encroachment through colonization
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33 330 by individual families carrying out swidden agriculture for subsistence or local markets for
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35 331 agricultural products and (ii) large-scale plantations of commercial crops for national or
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37 332 international markets, both in planned (according to legal requirements) and unplanned ways.
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42 333 In Amazonia, a clear correlation has been shown between proximity to a road and
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44 334 deforestation (Laurance *et al.* 2002). The expansion of the secondary road network (in large
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46 335 parts considered an unofficial or illegal activity; Barber *et al.* 2014) is often driven by the
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48 336 logging sector (Arima *et al.* 2005, Perz *et al.* 2007). Such roads have then been shown to
49
50 337 provide entry points to the forest for settlers seeking land (Uhl & Vieira 1989, Veríssimo *et*
51
52 338 *al.* 1995). According to remote sensing analyses, logging occurs within 25 km of detectable
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54 339 roads, and also the probability of logged forests being deforested is four-times higher than for
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56 340 unlogged (Asner *et al.* 2006). Spatially explicit examples of logging roads in Brazil that have
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3 341 been unofficially used for colonization are the Transiriri and the Transtutuí roads near Uruará
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5 342 (Arima *et al.* 2005) and other secondary roads in the state of Pará, such as north of São Félix
6
7 343 do Xingu (Mertens *et al.* 2002). Linear patterns of deforestation along logging roads have
8
9 344 also been observed in Central Africa (Mertens & Lambin 2000) and South-East Asia
10
11 345 (Kavanagh *et al.* 1989), emphasizing that logging roads can open up access to forests for
12
13 346 conversion in a wide range of contexts.
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17 347 Not all logging roads necessarily lead to an influx of subsistence farmers (Kummer &
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19 348 Turner II 1994). Kleinschroth, Healey & Gourlet-Fleury (2016) showed that only 12% of
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21 349 roads in a > 100,000 km² Central African forest area subject to commercial logging remained
22
23 350 open for more than 15 years. All other (mostly secondary) logging roads were transient,
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25 351 showing a median persistence of less than four years before recovery of vegetation cover
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27 352 (Kleinschroth *et al.* 2015). Forest areas in Africa with low human population density are
28
29 353 generally not ‘opened-up’ through conversion to agriculture following logging road
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31 354 construction (Wunder 2005). According to the von Thünen model (Angelsen 2007) it is
32
33 355 mostly access to markets that increases the likelihood of forest land being converted to
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35 356 agriculture. Logging operations might not be followed by in-migration at all in remote areas
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37 357 with poor soils that are sparsely populated (Chomitz & Gray 1996). Putz & Romero (2015)
38
39 358 note that in Indonesia swidden farmers continue to use abandoned logging roads after they
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41 359 have become impassable by vehicles, independently of the proximity to formal markets. The
42
43 360 time window for first colonization of forest by small-scale agriculturalists making use of
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45 361 abandoned logging roads may, however, be restricted to the first five years after logging
46
47 362 (Walker & Smith 1993). After that, the recovery of forest biomass makes forest conversion
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49 363 too costly. Generally, logging with its associated road construction cannot in itself be seen as
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51 364 the sole cause of encroachment by agriculturalists, as this often depends on official re-
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53 365 designation of the roads for public use or even large-scale government programs providing
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incentives for colonization (Nepstad *et al.* 2002, Barber *et al.* 2014, Alvarez & Naughton-Treves 2003). Governmental infrastructure development plans often simply exploit the opportunity provided by the previous construction of logging roads (Putz & Romero 2015).

In the Amazon logging can lead to feedback loops facilitated by roads, as logging activities attract a growing population and the presence of more people justifies more roads (Fearnside 1985). The attraction of human settlement generally results in an expansion of deforestation or severe forest degradation, eventually making way for the development of large-scale agro-industrial crop and livestock agriculture (Fearnside 1987). Logging reduces the immediately exploitable natural capital of forests, and thus their short-term value, providing an important economic incentive for conversion to cattle pasture, soy-bean or oil-palm crop land in Latin America and South-East Asia (Veríssimo *et al.* 1995, Uhl & Vieira 1989, Reid & Bowles 1997, Laurance & Balmford 2013). Thus, in the absence of appropriate land use planning, road construction can facilitate an expansion of the area converted to other land uses (Chomitz & Gray 1996). These problems are characteristic of areas where logging and agricultural frontiers are not clearly separated. As frequently observed in Amazonia, in the absence of appropriate planning controls, loggers and ranchers collaborate in road construction for timber exploitation followed by forest conversion to pasture (Schneider *et al.* 2000). Suggested measures to combat conversion of forest along logging roads include communicating evidence to policy makers of the value retained by logged forests for delivery of ecosystem services and conservation of biodiversity (Gaveau *et al.*, 2013; Edwards *et al.*, 2014), providing incentives through certification schemes, and stricter regulation of the granting of logging concessions (Oliveira *et al.* 2007).

The extent to which all or parts of the Trans-Amazonica or other highways in the Brazilian Amazon were initially built as logging roads and subsequently developed into major public roads is not documented. Nonetheless, the vast majority of public roads in

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2
3 391 tropical forest areas are likely to have started as logging roads (Francis E. Putz, pers. comm.),
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5 392 providing a lower cost option for increased public access. Loggers (conscious of the large
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7 393 costs involved) build roads where they are needed and where roadbuilding is feasible - the
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9 394 same criteria of feasibility apply to public road building, though the needs may be different.
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11 395 In the available literature, however, increased logging is often described as the consequence
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13 396 rather than the cause of road building and paving (Carvalho *et al.* 2001, Nepstad *et al.* 2001,
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15 397 Fearnside 2007, Johns *et al.* 1996), with the construction of roads providing a subsidy from
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17 398 the government to the timber industry (Uhl *et al.* 1997). Mertens *et al.* (2002) advocate the
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19 399 differentiation of numerous processes and actors in the case of Brazil: primary roads are
20
21 400 usually built by the state, while secondary road networks are often constructed by loggers,
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23 401 miners or dedicated colonization organisations. Roads built for a certain economic purpose
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25 402 are then regularly abandoned by their initial builders but then improved by colonists.
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27 403 Construction of new roads by large ranchers spontaneously colonising forest areas is the
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29 404 exception (Binswanger 1991) but once the process has started, these roads are sometimes
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31 405 subsequently used and extended by logging companies (Mertens *et al.* 2002). Uhl *et al.*
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33 406 (1997) documented these processes for the logging of “terra firme” forest, without forest
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35 407 management plans. Big companies, which have enough capital to invest in constructing their
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37 408 own roads, can operate relatively independently of existing road networks. Their business
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39 409 model is focused on highly selective logging restricted to the most valuable mahogany
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41 410 (*Swietenia macrophylla*) trees over large areas. In forest areas where such high-value tree
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43 411 species do not occur or have already been logged, this model is not commercially viable, so
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45 412 logging is restricted to areas where there are government-constructed roads. Here, high-
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47 413 intensity logging is often carried out by less-well-capitalised, small-scale local enterprises,
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49 414 followed by individuals using only a chainsaw who take the leftover trees. This cascade of
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3 415 uncontrolled exploitation, resulting from the initial road construction, generally leads to
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5 416 severe forest degradation and may pave the way for subsequent conversion to agriculture.
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8 417 Logging road impacts also have an anthropological dimension. For Amazonia,
9
10 418 concern has arisen that logging roads could provide unwanted access by outsiders to the land
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12 419 of indigenous communities, thus destroying their traditional way of life (Veríssimo *et al.*
13
14 420 1995, Uhl & Vieira 1989). In contrast, however, there is a more widespread (but often
15
16 421 neglected) demand from rural communities in tropical forest areas for improved access
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18 422 through new or better roads. In Central Africa, for example, Tiani *et al.* (2005) reported a
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20 423 positive perception by local communities of new road connections, facilitating access to
21
22 424 health care and education. Protecting the health of people living along roads does, however,
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24 425 require the management of road surface quality in a way that limits the risk of respiratory
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26 426 diseases from dust raised by heavy logging vehicles (Cerutti *et al.* 2014).
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30 427 ROAD PLANNING AS A COMPONENT OF SUSTAINABLE FOREST MANAGEMENT. —Road
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32 428 construction is one of the most costly components of selective logging operations (Holmes *et*
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34 429 *al.* 2002, Medjibe & Putz 2012). Therefore, investment in road construction and management
35
36 430 depends on the capital of logging companies (Gaveau *et al.* 2009). Best practice engineering
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38 431 guidelines for logging road construction in tropical forests have been published since the
39
40 432 1950's (reviewed by Kleinschroth, Gourlet-Fleury, *et al.* 2016). There have been few notable
41
42 433 developments in road engineering over this period, despite increased concern about the need
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44 434 to reduce negative environmental impacts. The bigger issue is that the existing best practice
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46 435 recommendations are rarely implemented, throughout the tropics (Putz *et al.* 2000).
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51 436 A landmark publication setting out recommendations for improved road planning,
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53 437 construction and maintenance is the FAO model code of forest harvesting practice (Dykstra
54
55 438 & Heinrich 1996), which played a crucial role in the development of reduced-impact logging
56
57 439 (RIL) guidelines (Pinard *et al.* 1995). The need for effective planning of road networks before
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3 440 they are constructed, in order to reduce residual stand damage, loss of biomass and damage to
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5 441 soil and watercourses, is a key component of RIL (Putz *et al.* 2008, Sist 2000). One
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7 442 component of this planning is to minimize road length density by optimizing the layout to
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9 443 reach the resource via the shortest path (Gullison & Hardner 1993, Picard *et al.* 2006).
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11 444 However, there is a potential trade-off between roads that are short and straight and those that
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13 445 are fitted to the topography to avoid steep slopes and the buffer zones of water courses
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15 446 (Negishi *et al.* 2008, Le Ray 1956), and even avoid large individual trees that are planned to
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17 447 be retained (Malcolm & Ray 2000). Overall, carefully planned road networks have been
18
19 448 shown to reduce forest damage by 40% compared with unplanned existing practice (Johns *et*
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21 449 *al.* 1996). Planning road networks that best combine minimisation of environmental damage
22
23 450 with economic efficiency requires high quality engineering based on accurate topographical
24
25 451 and edaphic/geotechnical information. Generally-available remotely-sensed imagery is not
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27 452 sufficient for accurate road planning, but imagery that penetrates the forest canopy down to
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29 453 ground level (in particular LiDAR) offers the prospect of a step-change improvement (Putz &
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31 454 Romero 2015).
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37 455 The width of road corridors from which trees are cleared is another important
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39 456 dimension for limiting environmental impact (Sist 2000). Forest canopy cover is commonly
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41 457 cleared on both sides of the road to increase the rate of sun drying of the road surface after
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43 458 rain (Sessions 2007). However, depending on road orientation the width required to
44
45 459 effectively achieve this can be quite narrow due to the high angle of the sun in the tropics
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47 460 (Wells 2002). The better a road is maintained and drained (e.g. through a parabolic camber
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49 461 throughout) the smaller can be the canopy opening needed to keep the surface sufficiently dry
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51 462 (Allouard 1954). In areas with notable rainfall seasonality restricting log extraction from core
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53 463 forest areas to the dry season would allow the use of low maintenance roads under a closed
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55 464 canopy. Reducing the width of the road corridor does increase the risk of vehicle collisions
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3 465 with wildlife, therefore it should be accompanied by enforced speed limitations (Sessions
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5 466 2007). Canopy bridges (achieved by large trees whose crowns meet across the road being
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7 467 retained unfelled) and infrastructure installed to increase the connectivity of animal habitats
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9 468 (e.g. tunnels below the road surface) are also recommended as a means of increasing the
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11 469 potential for wildlife to safely cross road corridors (Goosem 2007).
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15 470 Reducing the impacts of roads on forest biodiversity as a component of sustainable
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17 471 forest management requires the implementation of measures to prevent increased hunting and
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19 472 agricultural colonization following logging (Laurance 2001). Control of access to roads
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21 473 during and after logging is crucial (Bicknell *et al.* 2015), and requires both guarded barriers at
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23 474 strategic points in the permanent road network and the closure of logging roads (= “putting
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25 475 roads to bed”) after harvest (Mason & Putz 2001, Applegate *et al.* 2004). The corridor of
26
27 476 closed roads can be used to promote forest recovery, e.g. enrichment planting or other
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29 477 measures to promote the natural regeneration of timber trees (Kleinschroth, Healey, Sist, *et*
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31 478 *al.* 2016). Such tree plantations may also provide a psychological barrier against land
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33 479 colonization by swidden farmers (Putz & Romero 2015). Consideration should, nonetheless,
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35 480 be given to reopening roads that had been closed at the end of the previous logging operation
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37 481 for subsequent harvest operations in order to avoid the construction of new roads in the same
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39 482 area, or as a cost-effective alternative to opening up new forest areas for logging (Figure 3,
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41 483 Kleinschroth, Healey & Gourlet-Fleury 2016). If forest managers focus their management
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43 484 activities around a well-planned network of logging roads they can reduce both costs and
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45 485 unintended subsequent impacts (Putz & Romero 2015).
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51 486 To achieve sustainable forest management, companies that hold logging concessions
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53 487 should be held responsible for careful management of the quality and accessibility of their
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55 488 road networks. There is an argument that the infrastructure of tropical production forests
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57 489 should be managed like that of temperate forests, with a well-planned network of maintained
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2
3 490 permanent roads for management access (Francis E. Putz, pers. comm.). Here, roads are used
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5 491 not just during logging operations but also for interim monitoring, fire control and
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7 492 silvicultural interventions such as enrichment planting and thinning. These advantages,
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9 493 however, need to be weighed up against the risks of access for illegal hunting and
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11 494 encroachment that is often unregulated due to the institutional constraints in many tropical
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13 495 countries. Weak governance and lack of law enforcement also means that we cannot rely on
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15 496 protected forest areas to achieve conservation objectives. Therefore it is crucial to maximize
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17 497 the conservation value of the surrounding matrix of logged forest (Clark *et al.* 2009) by
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19 498 keeping it free of permanently accessible road that cause the fragmentation of forest habitat
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21 499 and a reduction in roadless space. The strategic planning of where to place permanent and
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23 500 temporary roads in the overall forest landscape is therefore crucial for achieving the best
24
25 501 compromise between retaining access for ongoing forest management, while minimising
26
27 502 long-term fragmentation and degradation in the highest priority areas for biodiversity
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29 503 conservation (Kleinschroth *et al.* 2017). The debate about “land sharing *versus* land sparing”
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31 504 also applies in the context of tropical timber production. The question here is in which areas
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33 505 should timber be harvested through separate one-off operations using temporary road
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35 506 infrastructure versus installing permanent road infrastructure (with its greater costs of initial
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37 507 capital and ongoing maintenance) to allow the forest to be managed for continuing higher
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39 508 timber yields, i.e. “sustainable intensification” (Putz & Ruslandi 2015). Such intensification
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41 509 in appropriate areas could help to ensure the protection of intact forests and roadless areas
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43 510 elsewhere, thus achieving the goal of land-sparing-logging (Edwards *et al.* 2014), as
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45 511 anticipated by the scenarios of Healey *et al.* (2000). For such protection of intact forests to be
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47 512 effective, region-wide landscape planning would be necessary.
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54 513 LOGGING ROADS AS FOREST HABITAT COMPONENTS. —Forest road corridors can be
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56 514 associated with five elementary functions: filter or barrier, conduit, source, sink and habitat
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(Forman 2003). The habitat type provided by logging roads is otherwise relatively rare in tropical forests (except along river channels or on very steep slopes subject to landslides), with its bare soil and greatly elevated light availability, which have been shown to increase leaf and fruit production in woody plants growing adjacent to road corridors (Johns 1988). Abandoned logging roads can even contribute to forest habitat diversity, which can increase some components of biodiversity, as shown for temperate forests (Coffin 2007). Wherever vegetation establishment is not prevented by severe soil degradation or continued road use, there is good potential for gradual recovery of ecosystem services, including provision of timber following tree regeneration. In regions with low intensity timber harvesting, enhanced levels of regeneration of light-demanding timber species have been observed on abandoned logging roads (Fredericksen & Mostacedo 2000, Nabe-Nielsen *et al.* 2007, Swaine & Agyeman 2008, Kleinschroth, Healey, Sist, *et al.* 2016). The road edge zone on either side of the track, from which trees are cleared during road construction, is a particularly suitable microhabitat for recruitment of timber species (Guariguata and Dupuy, 1997; Doucet, 2004). In contrast, in areas where soils are vulnerable to severe soil compaction or capping of the surface, especially where forests are subject to high-intensity timber harvesting such as the dipterocarp forests of South-East Asia, reduced levels of tree regeneration have been reported on abandoned roads and skid trails (Pinard *et al.*, 1996, 2000; Zang and Ding, 2009). Here, plants that can colonise degraded soils, such as certain fern species, may play an important role in ameliorating soil conditions and facilitating gradual forest recovery through vegetation succession. In their study in Peninsular Malaysia, Negishi *et al.* (2006) estimated that it would take up to 40 years for ferns to ameliorate substrate conditions sufficiently to enable taller plant species to establish a canopy that out-shades the ferns. Generally, the composition of vegetation recovering on abandoned logging roads may differ from that of old-growth

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3 539 forest for a long time, even if tree species diversity can reach comparable levels after 15 years
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5 540 (Kleinschroth, Healey, Sist, et al. 2016, but see Guariguata & Dupuy 1997).
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8 541 OUTLOOK. —We have identified major knowledge gaps concerning long-term
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10 542 impacts of logging roads. While there have been many studies of the immediate impacts of
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12 543 logging roads on animal community composition and movement, little is known about how
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14 544 this affects wildlife populations over the long-term. Much depends on how the barrier-effect
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16 545 and road-related threats such as poaching develop over time, and their impact on genetic
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18 546 diversity and exchange within populations. Given the practical limitations of field studies and
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20 547 the physical limits of remote sensing information, other innovative technologies should be
21
22 548 tested for inclusion in scientific studies. There is already a rapid expansion in the use of
23
24 549 camera traps and other electronic animal tracking devices in tropical forests (Harmsen *et al.*
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26 550 2010, Vanthomme *et al.* 2013), which could be deployed in the study of road impacts. An
27
28 551 example of more innovative approaches is the Rainforest Connection project
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30 552 (<https://rfcx.org/>) that places solar-powered smartphones equipped with software that can
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32 553 filter different audio-signals in rainforest canopies. These devices are programmed to send an
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34 554 alert when they record the sound of motors such as those of chainsaws or motorbikes,
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36 555 indicating illegal activities, and they could be used as a cost-effective method of monitoring
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38 556 poaching.
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44 557 The most common way to assess human impact on tropical forests over a large scale
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46 558 is by using roads as indicators (Laporte *et al.* 2007, Asner *et al.* 2009, Lewis *et al.* 2015).
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48 559 However, this approach does not differentiate between types of roads, although they can
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50 560 differ hugely in the severity and duration of impact that they indicate. Therefore, more effort
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52 561 is needed to understand and disentangle the impacts of roads depending on their location and
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54 562 connectivity in the overall network, the purposes that they are used for, how they are
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56 563 managed and maintained, and for how long they persist. There is a lack of quantification of
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3 564 the proportion of roads that have enabled long-term human encroachment *versus* those that
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5 565 have not, becoming impassable due to washouts of bridges and culverts, and recolonization
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7 566 by forest vegetation. For roads that have led to long-term forest degradation or conversion to
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9 567 agriculture, it would be important for forest policy to know what proportion were initially
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11 568 built for logging *versus* other purposes. This evidence would enable testing of whether road
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13 569 construction for logging invariably leads to subsequently illegal forest exploitation. It would
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15 570 also indicate whether and where there is a need to focus actions to prevent this occurring, in
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17 571 places where legal logging is allowed to continue.
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21 572 CONCLUSIONS. —The indirect impacts of logging roads on occurrence of fire,
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23 573 deterioration of water quality, conversion to agriculture and increased hunting are much more
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25 574 severe than the direct impacts of road construction and planned use on forest cover, soil and
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27 575 wildlife, as these are limited in persistence and in the surface area that they affect. To reduce
28
29 576 the subsequent indirect impacts, road access management is therefore crucial. For many
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31 577 tropical countries, however, it remains questionable how successful the enforcement of
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33 578 access restrictions can be, given the high demands for bushmeat and agricultural land. One
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35 579 solution to this problem is to intensify road construction and timber harvesting in suitable
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37 580 areas with high production potential, while sparing other areas of high conservation value
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39 581 from any new road construction.
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44 582 In the nexus of roads, hunting and deforestation it is generally difficult to determine if
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46 583 roads are endogenous or exogenous factors (Lambin *et al.* 2003). The question is, do roads
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48 584 affect just the precise location or also the overall quantity of forest conversion and hunting?
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50 585 So far, it seems that the construction of roads reduces the costs of such activities, thus making
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52 586 them affordable for more people. It remains unclear, however, what alternative sources of
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54 587 nutrition and livelihood are available for growing rural populations, and which productive
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56 588 land can be used to provide them. Much depends on the direction of transformations in
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society and how people's interaction with their natural environment changes, including forest conversion planned by governments. Poor governance, human population growth, migration and dependence on markets (from local to international) make this direction very hard to predict.

Roads are becoming an increasingly common component of tropical forests around the world. Given the great importance of logged forests for biodiversity conservation and carbon storage, and the high potential risks associated with the presence of roads, large-scale road planning needs to be placed near the top of the forest policy agenda. Monitoring the spatio-temporal dynamics of roads in tropical forests will provide crucial evidence for the goal of "development without destruction" (Lewis *et al.* 2015) through large-scale landscape planning. Its implementation is likely to require much more effective management of the accessibility of forest roads than is generally the case currently.

601

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605

606 **DATA AVAILABILITY STATEMENT**

Library entries for the full pre-selected literature database will be made available on DRYAD digital repository in *.bib, *.ris and *.xml formats.

609 **LITERATURE CITED**

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TABLES

TABLE 1: Widths of primary and secondary logging roads in tropical forests, separated between road track (the surface on which vehicles travel) and corridor (full width of forest cleared including on both sides of the track).

Track width (m)		Corridor width (m)		Country/ Continent	Forest certifi- cation	Reference
Primary	Secondary	Primary	Secondary			
6.6		24.7		Bolivia		Gullison & Hardner (1993)
5.2	4.6	13.3	10.5	Bolivia		Jackson <i>et al.</i> (2002)
	3.6		5.5 (5.3–5.7) ^a	Brazil		Johns <i>et al.</i> (1996)
4.3	5.1	10.1	9.8	Brazil		Feldpausch <i>et al.</i> (2005)
		12.5	3.0	Brazil		Uhl & Vieira (1989)
	3.3 (3.0–3.5) ^a		5.8 (5–6.5) ^a	Costa Rica		Guariguata & Dupuy (1997)
7		17		Cameroon		Hoeven (2010)
		25	20	Cameroon		Gideon Neba <i>et al.</i> (2014)
	5.3		17.2	Cameroon		Kleinschroth, Healey, Sist, <i>et al.</i> (2016), unpublished material
7.9	6.4			Central African Republic		Malcolm & Ray (2000)
6.4	5.1			Central African Republic		Durrieu de Madron <i>et al.</i> (2000)
6.8		22.6		Gabon		Medjibe <i>et al.</i> (2013)
	4.1		15.1	Gabon	FSC	Medjibe <i>et al.</i> (2013)
	7.9		66.6	Gabon	None	Medjibe <i>et al.</i> (2013)
		40	25	Republic of Congo		FAO (1995)
	7.7		25.3	Republic of Congo		Kleinschroth, Healey, Sist, <i>et al.</i> (2016), unpublished material

3-49		30	20	Central Africa	Estève (1983)
				Malaysia	Ziegler <i>et al.</i> (2007)
		32.75		Indonesia	FSC
					Griscom <i>et al.</i> (2014)
		31.78		Indonesia	None
					Griscom <i>et al.</i> (2014)
5.5	4	17.4	6.8	America ^b	
7.2	6	28.5	40.9	Africa ^b	
3.5		32.3		Asia ^b	
6.4	5.1	24.9	15.1	Global ^c	
5.8	5.26	24.1	19.3	Global ^d	

^a Mean and range (in brackets) of values given in the paper

^b Mean summarized for values of the respective continent

^c Median summarized for all values

^d Mean summarized for all values

TABLE 2: Proportion of the overall surface area of the forest (reference area defined for each study) cleared for road building.

Proportion of forest area cleared for road building	Country/Continent	Reference area	Reference
1%	Brazil	"Overall logged area"	Feldpausch <i>et al.</i> (2005)
8%	Brazil	"Total logged forest area"	Uhl & Vieira (1989)
1.05%	Bolivia	"Section of logged area"	Gullison & Hardner (1993)
2.1%	Bolivia	"Harvesting block"	Jackson <i>et al.</i> (2002)
1.3 (0.6–2)%	Brazil	"Total area of four harvest blocks"	Asner <i>et al.</i> (2002) Pereira <i>et al.</i> (2002)
0.7%	Belize	"One-year logging coupe"	Arevalo <i>et al.</i> (2016)
2%	Cameroon	"Annual allowable cut area"	Gideon Neba <i>et al.</i> (2014)
0.74%	Cameroon	"Average across seven logging concessions"	Kleinschroth, Healey, Sist, <i>et al.</i> (2016)
0.8%	Central African Republic	"Annual allowable cut area"	Durrieu de Madron <i>et al.</i> (2000)
6.4%	Gabon	"Logged section of overall forest area"	White (1994)
1.7%	Republic of Congo	NA	FAO (1995)
0.8%	Republic of Congo	"Average across four logging concessions"	Kleinschroth, Healey, Sist, <i>et al.</i> (2016)
1.84 (1.3–2.4)%	Central Africa ^a	NA	Estève (1983)
4 (3.3–4.7)%	Indonesia ^a	"Logging unit"	Pinard <i>et al.</i> (2000)
4.8%	Malaysia	"Logging compartment"	Johns (1988)
0.6–8%	America ^b		
0.74–6.4%	Africa ^b		
3.3–4.8%	Asia ^b		
1.7%	Global ^c		
2.48%	Global ^d		

^a Mean and range (in brackets) of values given in the paper

^b Range (minimum and maximum values) summarized for respective continent

^c Median summarized for all values

^d Mean summarized for all values

FIGURE LEGENDS

FIGURE 1: Example of a secondary logging road in Republic of Congo annotated with cross-section measures and their respective names used in the text.

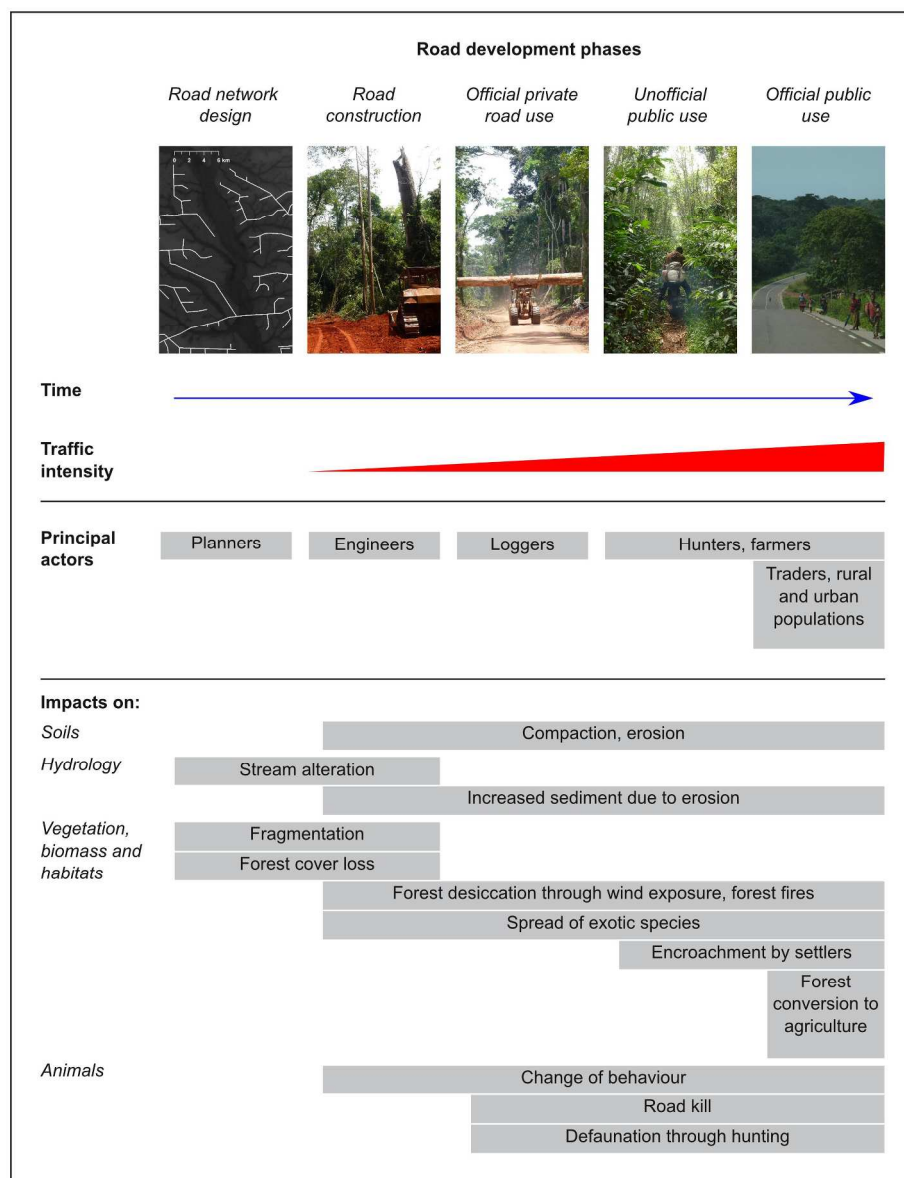
FIGURE 2: Conceptual model of the temporal evolution of logging roads, principal actors, potential impacts linked to each phase and measures to mitigate them.

FIGURE 3: Comparison of the impact intensity of two hypothetical logging road development trajectories, depending on follow-up use (see Figure 2) or successful closure after logging until the next logging cycle. A darker shading of the orange bar indicates higher impact intensity, based on an estimated accumulation of impacts described in the main text.



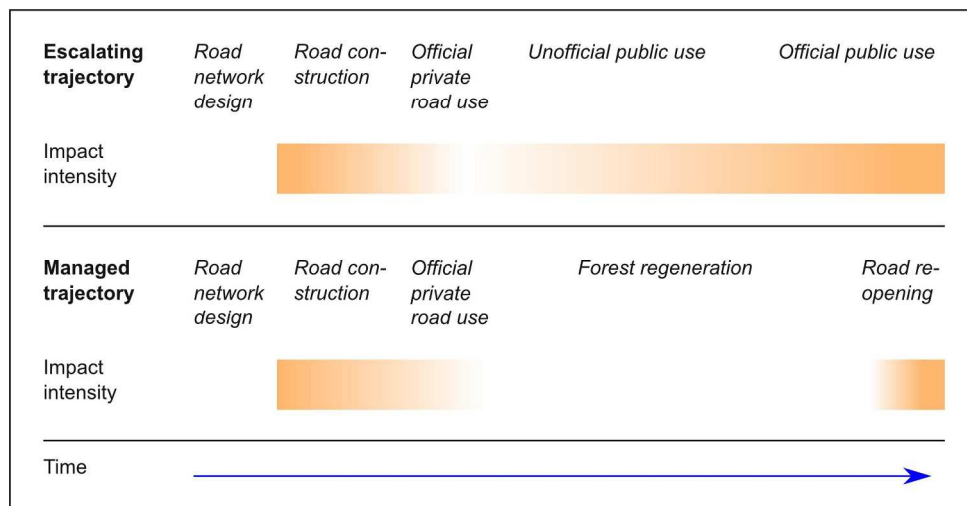
Example of a secondary logging road in Republic of Congo annotated with cross-section measures and their respective names used in the text.

Figure 1
207x206mm (300 x 300 DPI)



Conceptual model of the temporal evolution of logging roads, principal actors, potential impacts linked to each phase and measures to mitigate them.

Figure 2
222x285mm (300 x 300 DPI)



Comparison of the impact intensity of two hypothetical logging road development trajectories, depending on follow-up use (see Figure 2) or successful closure after logging until the next logging cycle. A darker shading of the orange bar indicates higher impact intensity, based on an estimated accumulation of impacts described in the main text.

Figure 3
211x112mm (300 x 300 DPI)